AIAA SciTech Forum
11–15 & 19–21 January 2021, VIRTUAL EVENT
AIAA Scitech 2021 Forum

10.2514/6.2021-1273

Forecasting the Global Supersonic Business Aviation Flight Movements Up to 2050

Jiajie (Terry) Wen *
Aerospace Systems Design Laboratory at Georgia Tech Lorraine (ASDL@GTL), International Research Lab Georgia Tech-CNRS, UMI 2958, Georgia Tech Lorraine, 57070 Metz, France

Turab A. Zaidi †
Aerospace Systems Design Laboratory at Georgia Tech Lorraine (ASDL@GTL), Georgia Tech Lorraine, 57070 Metz, France

Dimitri N. Mavris‡
Aerospace Systems Design Laboratory (ASDL), School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA, 30332, USA

Business aviation is typically the primary travel mode chosen by ultra-high-net-worth (UHNW) individuals and top executives. Business aviation passengers prefer the exclusivity associated with business jets, and are typically constrained by time and not cost when traveling. Numerous studies have found that business jets are worthwhile investments for corporations to increase connectivity and boost productivity. With the resurgence of efforts to bring back supersonic civil transport in the past decade, the supersonic business jet (SSBJ) poses to create significant value as a means of transport for these time-constrained travelers. However, the demand forecast for supersonic business aviation is not well-addressed in the publicly available literature. To better understand the potential size of the supersonic business aviation market and the extent of the future supersonic business flight network, this study utilizes a unique methodology that combines top-down and bottom-up approaches to forecast global supersonic business flight movements up to 2050.

I. Introduction

Among the remarkable achievements of mankind during the first century of aviation, the design, manufacturing, and service of the supersonic airliner Aérospatiale/BAC Concorde is certainly a noteworthy one. In 2003, the Concorde was retired for a confluence of reasons, including excessive noise, high operating costs, and weak passenger demand [1]. Although the Concorde is no longer flying, it remains a symbol of engineering achievements from the 20th century. The human desire to fly supersonically did not retire with the Concorde, however. The past decade has seen multiple efforts to re-introduce supersonic flight for both commercial and business operations. The business aviation market might be a better (re-)launch point for civil supersonic flight in the 21st century, since business aircraft are generally smaller with lower passenger capacity, and do not require high aircraft utilization (flight hours per year) or high passenger load factor (percentage of seats filled per flight) to be of value to the owners and customers. The upcoming supersonic business jets will most likely come with a hefty price-tag, but some customers value the potential time savings more than the cost associated with it. In the past two decades, numerous market studies have been conducted on SSBJ aircraft demand, and the report published by George Mason University provides a great summary of these studies [2]. In terms of supersonic flight demand forecasts, existing literature mainly focused on commercial operations [3–6]. Interestingly, [4] investigated a special case of operating supersonic business jets as airliners for the commercial market. However, to the authors' knowledge, there are no supersonic business movement forecasts in the public domain. To better understand the significance of supersonic business jets' entry into the business aviation market, this study presents a methodology that forecasts the supersonic business flight network and the number of flight movements based on subsonic business aviation movement data and SSBJ vehicle demand.

*Researcher, ASDL@GTL and CNRS, UMI 2958, Georgia Tech Lorraine, AIAA Member
†Lecturer, Head of ASDL@GTL and Associate Faculty, Georgia Tech-CNRS UMI 2958, Georgia Tech Lorraine, AIAA Member
‡S.P. Langley Distinguished Regents Professor and Director, ASDL, School of Aerospace Engineering, Georgia Tech, AIAA Fellow

II. Commercial Aviation vs. Business Aviation

In this study, business aviation is broadly defined as unscheduled movements (as opposed to commercial, scheduled movements). These unscheduled flights do not have to be flown for business purposes only. With supersonic business jets such as Aerion AS2 planning to enter service in the next decade, it is imperative to evaluate the impact of SSBJs on business aviation. To have a better understanding of business aviation, it is helpful to compare it with commercial aviation.

A. Importance of Business Aviation

In 2016, the European Business Aviation Association (EBAA) commissioned a study to analyze and quantify the impact of business aviation industry on the European economy [7]. It summarized the benefits of business aviation in three major categories: economic growth, business efficiencies, and improved connectivity. For the passengers, it creates significant time savings over commercial travel (2 hours on average). In addition, a business aircraft is usually able to create a much more secure, distraction-free work environment for the travelers on-board [8]. A survey showed that when business travelers are flying on a business aircraft, 72% of them spend time on work-related tasks. This number is only 31% when they are flying commercial [9].

B. Aircraft Utilization

Commercial airlines are always trying to find ways to improve their operating efficiency and maximize aircraft utilization. MIT's Airline data project [10] processed data published by the U.S. Bureau of Transportation Statistics [11] and showed that U.S. carriers have averaged over 10 daily block hours of utilization on their aircraft within the operating fleet. This metric translates to more than 3,500 hours of utilization per year on average for an active commercial aircraft.

Business aircraft utilization is much lower than commercial airliner's utilization. Data published quarterly by Jet Support Services, Inc. (JSSI) shows that in recent years, large-cabin business jets record about 35 flight hours per month, or 420 per year [12]. This discrepancy between business and commercial aircraft highlights a major difference in operations, and having a good understanding of these differences is an important part of the forecasting exercise.

C. Airport Considerations

1. Number of Airports Served

One of the main reasons that a business passenger chooses to fly with business aircraft is to reach destinations that an airline does not serve [9]. Research by the National Business Aviation Association (NBAA) suggests that in the United States alone, business aviation serves 10 times the number of airports (more than 5,000) served by commercial airlines (about 500) [8]. For Europe, the case studies presented in an EBAA study [13] showed that airports served by business aviation increased 300-600% compared to commercial airports served for most representative cities. Being able to arrive at a regional airport closer to the destination leads to significant time savings [7].

2. Airport Infrastructure

Airports that cater to business aviation and general aviation tend to have fewer and shorter runways compared to those major hub airports for commercial services, ranging from 6000-7500 ft compared to over 8000 ft for most commercial airports. Additionally, it is common to have lower weight limits on the aircraft operating at these airports. For example, the Teterboro Airport (TEB), one of the most popular business aviation airports in the United States, has an aircraft gross weight limit of 100,000 lbs. Exceptions must be approved to operate aircraft with maximum take-off weight higher than this limit at a reduced weight level [14]. However, such restriction is imposed due to noise concerns, and not because of runway pavement's load-bearing capability.

III. Business Aviation Market

A. Proposed Supersonic Business Jet - Aerion AS2

The Aerion AS2 is a supersonic business jet currently under development, with the targeted entry-into-service year of 2027 [15]. The company aims to achieve greater than 5,000 nautical miles (nmi) of range at a subsonic cruise Mach number of 0.95, and a Mach 1.4 supersonic cruise range targeting about 4,200 nmi [16]. How will the introduction of

AS2 affect the existing business jet market is uncertain. Some believe that the AS2 will mainly compete with subsonic business jets with mid-size to large cabins for market share. However, it might be more likely for these aircraft to create a brand new market segment due to their unique capability of supersonic flight.

B. 2nd Generation, Low Boom SSBJ

The AS2 supersonic business jet proposed by Aerion is not of low-boom design, since such technology is not yet mature enough to be incorporated on a production aircraft. As a result, the AS2 will cruise over-land at Mach cut-off speed if regulation permits. Otherwise, when flying over-land, the aircraft will cruise at a Mach number below 1.0. However, in the past decades, boom reduction has been a popular topic in supersonic research, with flight tests conducted with modified aircraft [17, 18]. The X-59 low-boom flight demonstrator designed by NASA and Lockheed Martin is currently being manufactured, with its first flight planned for late 2021 [19]. The goal of this project is to validate the low-boom aircraft design and gather community data in response to the sonic boom levels.

C. Business Jet Customers and Utilization

Compare to the single-aisle and twin-aisle airliners, business jets can have a wider range of customers. According to a subject matter expert, early adopters for SSBJs will likely be similar to the ultra-long-range jet customers [20]. The specific categories of customers and their corresponding market share are reproduced in tabular form below:

Table 1 Potential Supersonic Business Jet Customers and Their Market Share

Potential SSBJ Customers	Market Share
Corporate Operators	32%
Ultra-High-Net-Worth Individuals and Private Corporations	25%
Aircraft Management, Charter, and Fractional	24%
Government and Head-of-State	19%

It is also natural to believe the different use cases of these entities will result in different degrees of aircraft utilization. For example, aircraft operated by charter and fractional operators are likely to see higher annual flight hours than aircraft owned by a UHNW individual.

D. Subsonic Business Aviation Movement Data

1. Data Summary

Business aviation flight movement data in the public domain is extremely limited. Rough movement data for business aviation flights leaving Europe can be found in the European Business Aviation report [13], and EUROCONTROL has published trip distance distribution for European business aviation flights [21]. However, these data provide very limited information, and such data was not found for other markets, including the United States. Being able to analyze business aviation traffic pattern is crucial, thus the research team decided to pursue non-public data.

FlightAware is a global aviation software and data services company and one of the few that can provide non-scheduled flight movement data. To analyze the traffic pattern of medium to ultra-long-range (3,000 – 7,500 nmi) jets, flight movement is queried for the entire year of 2019 and aggregated on the origin-destination airport level using FlightAware's custom report service [22]. A new supersonic business jet might be more expensive than even the most premium ultra-long-range subsonic jets, but SSBJs will not replace them because of limited range. The FlightAware data is used to construct the flight movement patterns, and this will enable the identification of regions with higher potential for SSBJ flight movement. The histogram and cumulative distribution of global number of movements vs. great circle distance (GCD) for trips flown by all medium to ultra-long-range (ULR) jets in 2019 are shown in Figure 2 below. The number of movements is reported in thousands.

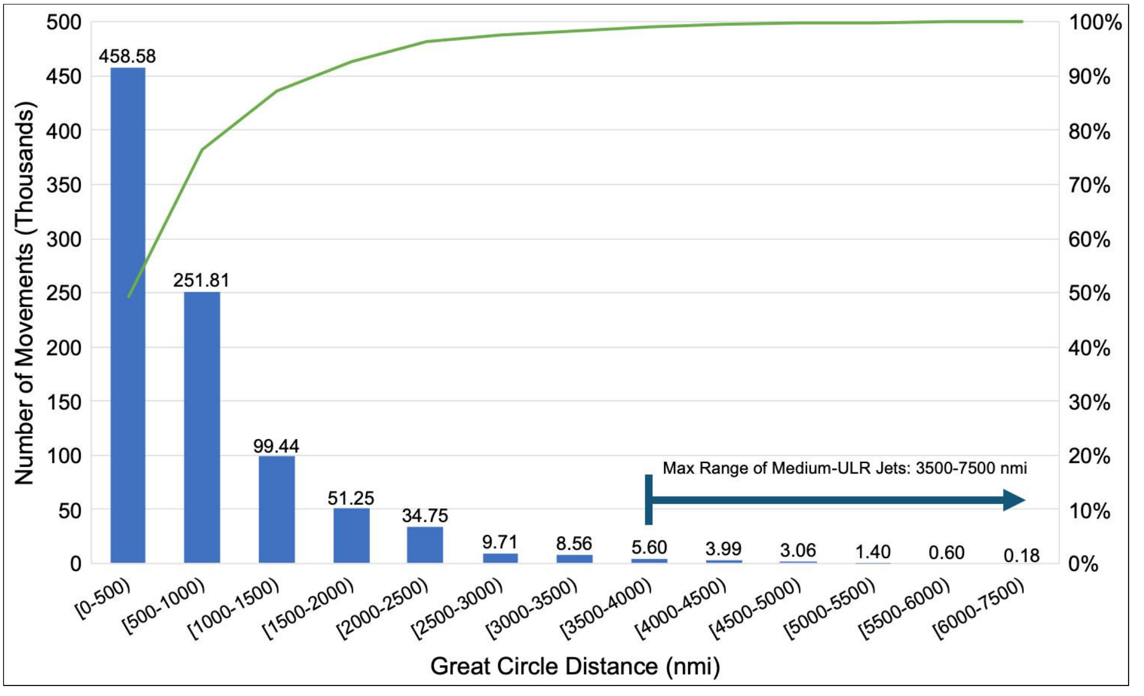


Fig. 1 Flight Movement vs. Great Circle Distance for Medium-ULR Jets

One key observation is that business aircraft are flown way below their maximum range, since GCD is heavily skewed towards lower values. However, this type of trend is quite common for trip distributions. Additionally, the researchers did not find any noticeable correlations between business jet size vs trip distance - the larger jets are flown on shorter journeys as frequently as the smaller jets.

Taking a closer look at the movements below 500 nmi, the 100-200 nmi category has the highest number of movements. Additionally, according to FlightAware, the top 20 routes globally (ranked by the number of flights) are all U.S. domestic routes, and 10 of them have great circle distances less than 200 nmi. Within these 10, 8 of them are greater than 150 nmi, with the other two being only about 21 nmi. As a result, the researchers categorized flights above 150 to be regular flights, and flights below this threshold to be overhead flights. Overhead flights could be flown due to maintenance purposes, charter companies repositioning their aircraft, and many others. It makes little sense for an SSBJ to operate on such short routes, but these flights are sometimes unavoidable.

2. *FlightAware Data Coverage*

FlightAware collects flight movement data using the Automatic Dependent Surveillance-Broadcast (ADS-B) technology. Even though the ADS-B data coverage has been steadily growing, only 10% of private jets are currently equipped with ADS-B transponders [23]. Furthermore, certain regions have worse coverage than others. To better understand this issue, the movements are grouped into region-pairs based on a set of regions. Since the data only reports the number of movements between an airport pair and the aircraft type, the actual trip purpose or aircraft ownership information is unknown. In this study, the researchers assume that an aircraft based in one region will only be flown on routes related to that region. For example, an aircraft based in North America will not be flown between Asia and Oceania. Even though this is not always true in the real world, it should still be a valid assumption.

Table 2 below shows the estimated FlightAware data coverage for different regions based on data compiled from various sources [12, 24–27]. For the region definition, Europe includes the Commonwealth of Independent States, Asia includes the Middle East, Latin America includes Mexico, the other central American countries, and South America. Mainland China is considered separately from Asia due to higher forecasted economic and aviation growth. The FlightAware flight hours represent the aggregated flight hours for aircraft based in each region. The research team was not able to obtain more detailed data for region-level annual flight hours. However, the relative data coverage between different regions still provides useful insight.

Table 2 FlightAware Data Coverage Estimates

Region	Medium-ULR Jet Fleet Size	Annual Utilization (hours)	Total Estimated Medium-ULR Jet Annual Flight Hours	FlightAware Flight Hours	Estimated FlightAware Data Coverage
N. America	7,014	312	2,188,324	1,333,065.8	60.9%
Europe	1,646	480	790,045	172,002.9	21.8%
Asia	873	300	261,792	44,464.2	17.0%
China	259	300	77,688	8,367.5	10.8%
L. America	1,009	228	230,029	89,330.8	38.8%
Oceania	97	300	29,028	15,229.1	52.5%
Africa	285	360	1027,73	11,923.4	11.6%

Table 2 shows that the data coverage for Europe, Asia, mainland China, and Africa is quite poor, with their logged flight hours out of proportion compared to the fleet size. The estimated annual flight hours and the data coverage are only for the year 2019. As the fleet size grows over time, the flight hours in different regions will grow at different rates, changing the flight movement pattern. To better understand the actual flight movement pattern among different regions, it is important to amend the data coverage issue so that a more representative flight movement pattern can be obtained for both the current and future data. This is explained later in section V.E.

IV. Overview of Methodology

A. Forecasting Formulation

Two different approaches are commonly used when forecasting flight movements: top-down and bottom-up. The top-down approach would either start with projected aircraft demand and estimate the resulting flight movements, or correlate the evolution of the aviation industry with economic parameters such as GDP per capita, corporate revenue, and income distribution. The bottom-approach, on the other hand, typically identifies a possible network from an existing one by applying filtering criteria. It is common to see the bottom-up approach used on commercial aviation forecasts because the variability in passenger demand is generally low, there is a clear traffic pattern, and aircraft utilization is consistent. Comparing to commercial service, business aviation can be characterized by many different use cases, less predictable traffic, and irregular aircraft utilization.

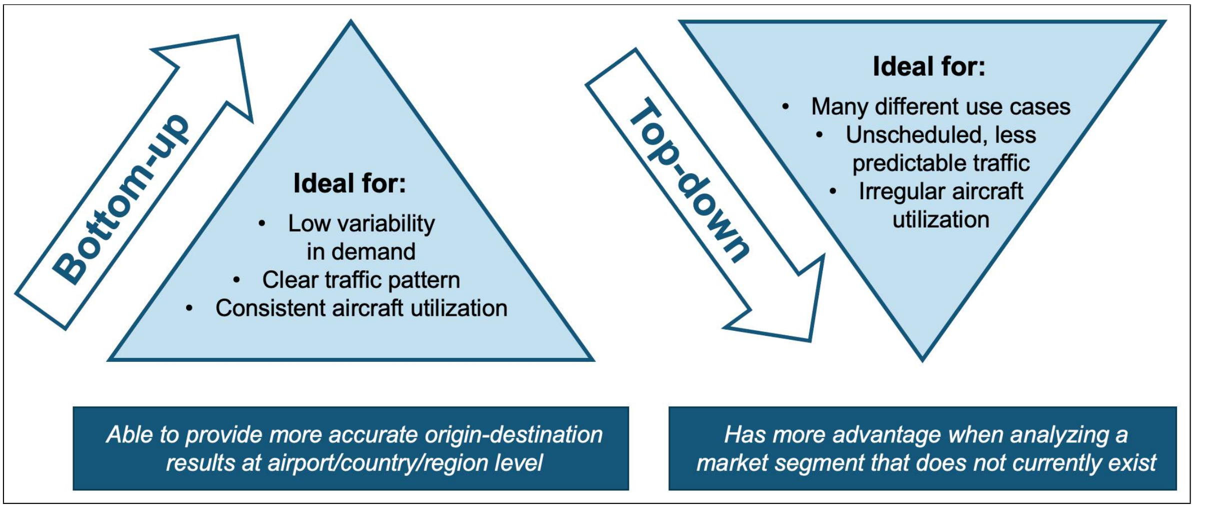


Fig. 2 Top-Down vs. Bottom-Up Methodologies for Aviation Forecasting

When formulating the methodology for this study, the goal was to take advantage of the strength of both approaches, since the study outcome should be able to provide the forecasted routes suitable for SSBJs and the frequency of flights. Additionally, the top-down approach provides the necessary flexibility needed in this study. The result is a hybrid methodology, described in the figure below:

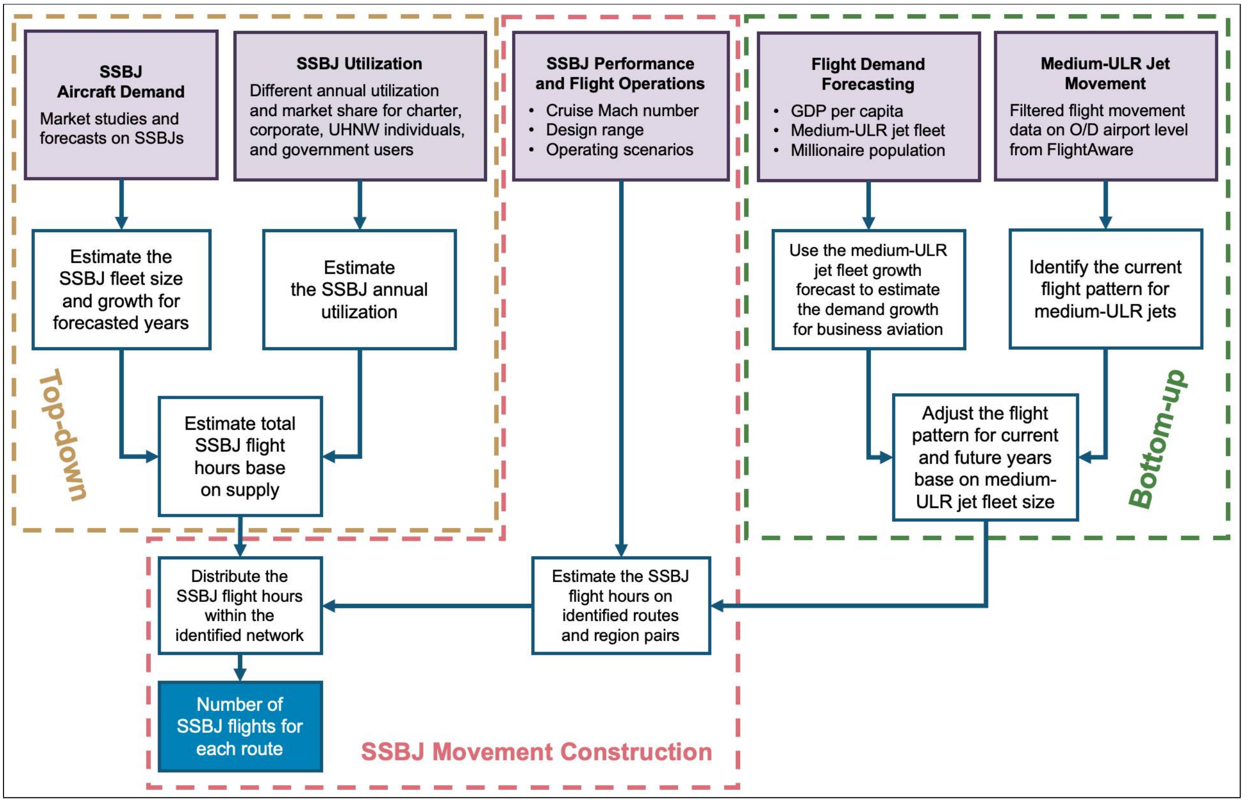


Fig. 3 SSBJ Flight Movement Forecasting Methodology

The five purple boxes shown on top are the essential elements, which are also inputs to the methodology. The white boxes are the main steps taken to arrive at the final result (shown in the blue box), which consists of the route list and number of flights. The entire methodology can be divided into three main sections, illustrated using yellow, green, and red dashed lines. The dashed lines on this flowchart also highlight the fact that the overall approach used to construct this methodology is not simply the top-down or the bottom-up method. Instead, it is a hybrid approach that uses the benefit of both to their advantage. On the left side, the top-down approach starts with SSBJ aircraft demand. On the very right, the bottom-up approach originates from the subsonic movement data. This hybrid approach allows origin-destination (O/D) results at either the airport-level or the region-level to be reported, and it also compensates for regions where flight movement data coverage is poor.

This study assumes that the combination of unique performance capability and the high price tag of SSBJs will create a new market segment that has a negligible impact on existing subsonic business aviation, and the supersonic movement pattern will mostly be analogous to subsonic movements (while constraints that are unique to SSBJs will be considered).

B. Scenario-Based Approach

Because of the inherent uncertainty when forecasting future events, a common approach in such studies is to define scenarios to capture a possible range of outcomes. For supersonic business aviation demand forecasting, different scenarios can be found in each of the five key elements. Table 3 below summarizes the differences between the two scenarios. These assumptions will be explained in greater detail in the following sections.

Table 3 Flight Movement Forecasting Scenario Assumptions

Attribute	High Demand	Low Demand	Notes
SSBJ Aircraft Demand	Higher	Lower	The SSBJ vehicle demand is estimated from the results of various market studies. The introduction of a low boom SSBJ increases vehicle demand for the high demand scenario.
SSBJ Utilization	Higher % of Charter Owners	Higher % of UHNW Individual Owners	Annual utilization for SSBJ is assumed to be comparable to large subsonic jets. Even if more maintenance time is required, it is not likely to affect aircraft utilization (since utilization is low). However, the ownership share is varied between the two scenarios.
Supersonic Overland Flight Restriction	M=1.15 up to 2040, then M=1.4	M=0.95 up to 2040, then M=1.15	The high demand scenario assumes supersonic overland flight regulations will be in place by 2035. 2nd-generation low boom SSBJs will be allowed to cruise at full supersonic speed over land. The low demand scenario assumes that supersonic overland flight will only be permitted at Mach cut-off speed in 2040.
Business Aviation Demand Growth	Higher	Lower	The business aviation demand growth (estimated using medium-ULR jet fleet growth) will vary for different regions and scenarios.
Short Overhead Flights (For Repositioning, Maintenance, etc., < 150 nmi)	50% Less than Subsonic Business Flights	66% Less than Subsonic Business Flights	All types of business jets are often used on very short flights (less than 150 nmi). These flights are flown to transport passengers, to reposition the aircraft (to better serve the clients), or to reach specific maintenance facilities. It makes less economic sense for an SSBJ to operate on these routes, but they are sometimes unavoidable.

V. Five Essential Elements of the Forecasting Methodology

As explained previously, estimating the flight demand for supersonic business aviation is difficult because there are many different ownership types and trip purposes. In addition, the usage of SSBJ does not always have to be justified with substantial time savings. The forecasting methodology should also account for the unique characteristics of business aviation. During methodology formulation, the researchers identified five essential elements and some key research questions that each element is trying to answer. These are summarized in Table 4. The next few sub-sections examine each element in more detail.

Table 4 Essential Elements and Key Research Questions for the SSBJ Forecasting Methodology

Essential Elements	Key Research Questions
SSBJ Aircraft Demand	How many SSBJs will be flying? When will they enter the market?
SSBJ Utilization	How often will SSBJs be flown? What would be the trip purpose?
SSBJ Performance & Flight Operations	What is the speed and range of the SSBJ? Will regulations allow SSBJ to fly supersonically overland?
Flight Demand Forecasting	How to forecast the growth in business aviation? How will business aviation flight demand grow?
Medium-ULR Jet Movement	How are subsonic business jets flown currently? How will the flight movement pattern evolve?

A. SSBJ Aircraft Demand

In the past 20 years, many market studies have been carried out to predict the demand for supersonic business jets [2]. The results are reported for a period of either 10 or 20 years, with the number of aircraft on the order of several hundred. Since the research on this topic has been abundant, instead of re-evaluating the SSBJ vehicle demand, these market forecasts are simply consolidated into low and high SSBJ demand scenarios. However, instead of a constant annual production rate, production ramp-up is estimated from aircraft delivery data.

1. Production Ramp-Up

whenever a new product is introduced, there is usually a production ramp-up phase before the factory reaches the peak annual production rate. Since ultra-long-range jet is the most complex type of business jets currently in production, future delivery data for ultra-long-range jets published by Jetcraft [28] is compiled and analyzed to estimate production ramp-up for SSBJs. Jetcraft data shows that annual production for most ULR jets becomes stable after 5 years. The averaged annual and cumulative production ramp-up estimates are shown in Figure 4:

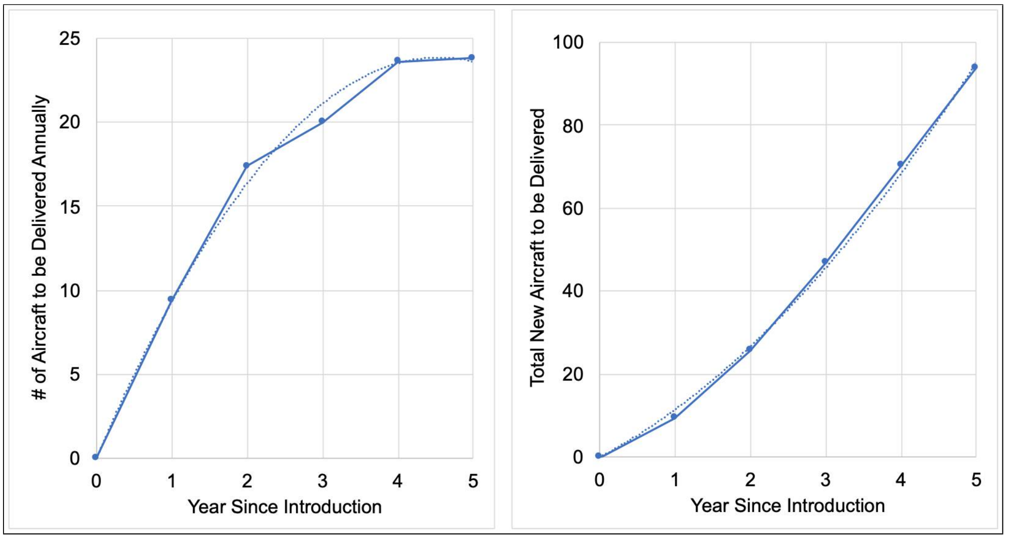


Fig. 4 Annual and Cumulative Production Ramp-up Estimates for Ultra-Long-Range Business Jets

2. Entry-Into-Service and Product Life Cycle

This study is mainly interested in the SSBJ flight movements between 2035 and 2050. However, the target entry-into-service (EIS) year for the Aerion AS2 is 2027 [15], many years before the forecasting period. As a result, the supersonic business aviation market's development prior to 2035 should also be analyzed. The high demand scenario assumes that the EIS year is identical to Aerion's estimate of 2027. For the low demand scenario, taking possible delays into account, the EIS year is assumed to be 2030.

Another factor related to SSBJ production is the length of its product life cycle. Looking at current offerings from Bombardier, Dassault, and Gulfstream, many of the medium to ultra-long-range jet families have been in the market for more than 20 years, with incremental upgrades brought to the market every few years. Since small upgrades (either in performance or features) are unlikely to have a major impact on the forecast, the researchers assume that the same SSBJ model (referred to as the 1st generation SSBJ) will be in production beyond 2050. This assumption is consistent between the high and low demand scenarios.

3. Incorporating Low Boom SSBJ in Aircraft Demand

Because of the on-going research efforts and the willingness of regulatory bodies to update the regulations for supersonic flight, there are enough reasons for the research team and the Topic Leader to believe that a second-generation SSBJ with low boom design will be introduced during the forecast time-frame, enabling full speed supersonic flight over-land. In addition, the introduction of a second-generation SSBJ is more likely to occur in the high demand scenario since there are more incentives to bring new technology and improvements to a market with greater potential. As a result, this study assumes that a second-generation SSBJ will be introduced in 2040 for the high demand scenario only. The fleet growth is also assumed to be 600 aircraft over 20 years.

4. Outcome of the SSBJ Aircraft Demand Analysis

The figure below shows the final outcome of the first essential element, the SSBJ aircraft demand analysis.

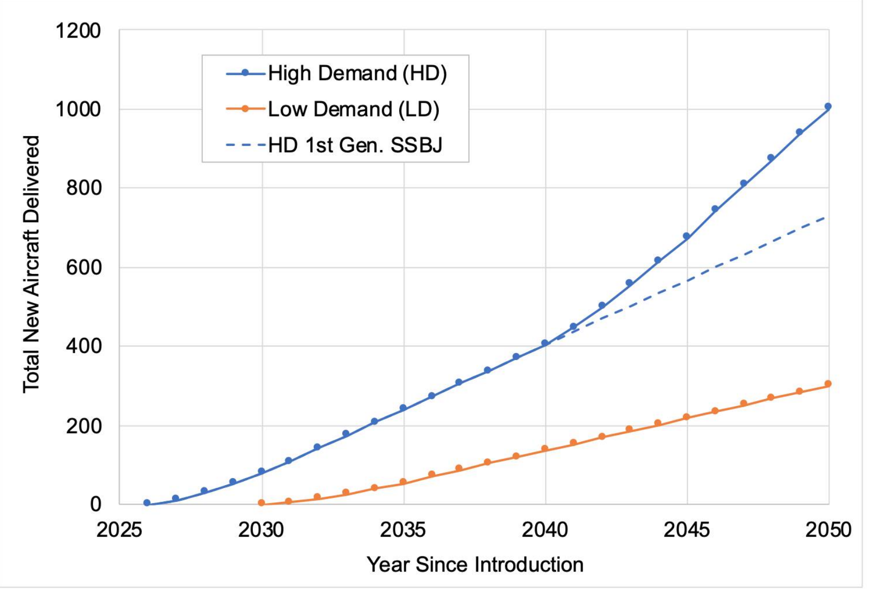


Fig. 5 Forecasted SSBJ Vehicle Demand Progression

B. SSBJ Utilization

1. Aircraft Utilization by User Group

As mentioned in section III.C, utilization for large-cabin jets is about 420 flight hours per year on average [12]. This value is one order of magnitude lower than commercial airliner utilization and likely represents the average for all user groups. For charter companies, data published by AIN online shows that annual utilization ranges between 275 and 1,637 hours across the top 25 charter companies in 2018 [29]. Even though there is a wide spread among different companies, the top 6 operators that account for half of the total flight hours on the list have an average aircraft utilization of roughly 600 hours per year.

Designing a business jet capable of supersonic cruise will likely lead to greater complexity and more stringent maintenance requirements. However, this study assumes that the annual utilization of an SSBJ will be similar to that of current business jets, since the maintenance downtime is unlikely to affect the relatively low aircraft usage. For corporate operators and government (user groups with medium usage), the annual utilization is assumed to be the nominal value of 420 hours. For ultra-high-net-worth (UHNW) individuals and private corporations, the researchers were unable to find published data to estimate annual utilization. Thus, after discussion with subject matter experts, 150 hours is assumed.

2. SSBJ User Group Ownership Breakdown

Even though the annual aircraft utilization is not affected by scenario variation, the ownership share certainly can be. The high demand scenario sees better adaptation and usage of SSBJs, which means charter and fractional operators are likely to have a higher ownership share. If the benefits of SSBJs turn out to be limited (e.g. insignificant time advantage at substantially higher operating costs), then charter and fractional operators might prefer not to incorporate too many SSBJs into their fleet. However, the UHNW individuals could be more drawn to the exclusivity of the aircraft and the capability for cruise speed. These preferences will be reflected in the low demand scenario.

The nominal ownership share for SSBJs was mentioned in Section III.C. In the high demand scenario, +5% is applied to charter and fractional companies, and -5% is applied to UHNW individuals and private corporations. The opposite is done for the low demand scenario. The pie charts in Figure 6 visualize the different ownership breakdown.

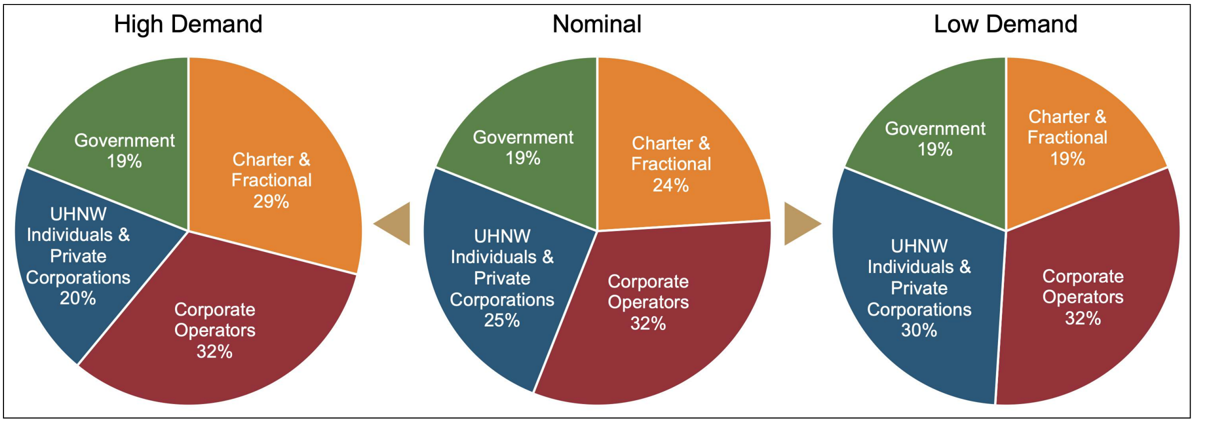


Fig. 6 High and Low Demand Scenarios for the SSBJ Ownership Breakdown

3. Outcome of the SSBJ Utilization Analysis

After taking the aforementioned factors into consideration, the annual utilization for high and low demand scenarios are summarized in Table 5:

Table 5 SSBJ Average Annual Utilization

Scenario	High Demand	Low Demand
Average Annual Utilization (hrs/year)	418	373

C. Flight Operation, Projected Timeline, and Trip Time Estimation

1. Supersonic Aviation Timeline

This study considered three different operating scenarios when the SSBJ is flying overland: Subsonic cruise at Mach 0.95, Mach cut-off cruise (estimated to be at Mach 1.15), and full supersonic cruise at Mach 1.4. It is also assumed that the same rules are imposed globally.

The high demand scenario defines a more optimistic timeline for the flight operation. In 2019, the Federal Aviation Administration (FAA) proposed to update the requirements to apply for civil supersonic flight authorization in the U.S. [30]. This will encourage flight testing above Mach 1, allowing researchers to gather data, paving the way for a new set of regulations. Additionally, there is also a proposed rule for the landing and take-off (LTO) cycle noise standards that will apply to supersonic business jets [31]. These actions by the U.S regulatory bodies suggest that they are moving forward with necessary changes that will enable a supersonic civil aircraft to operate. Once progress has been made in the United States, the researchers assume that regulatory bodies in other regions of the world will soon follow and update their regulations. Because of the continued research efforts in low boom design, this technology could be incorporated on the second-generation SSBJ in 2040 for the high demand scenario, enabling full supersonic cruise.

The low demand scenario assumes the regulation that enables supersonic over-land flight (at Mach cut-off speed) encounters resistance either due to technical aspects of Mach cut-off flight or due to public acceptance issues. As a result, Mach cut-off flight will not be possible by the entry-into-service year of 2030. Instead, the aircraft would have to fly subsonically over-land until 2039 and switch to Mach cut-off flight in 2040. The timelines for different operating scenarios are summarized in Figure 7:

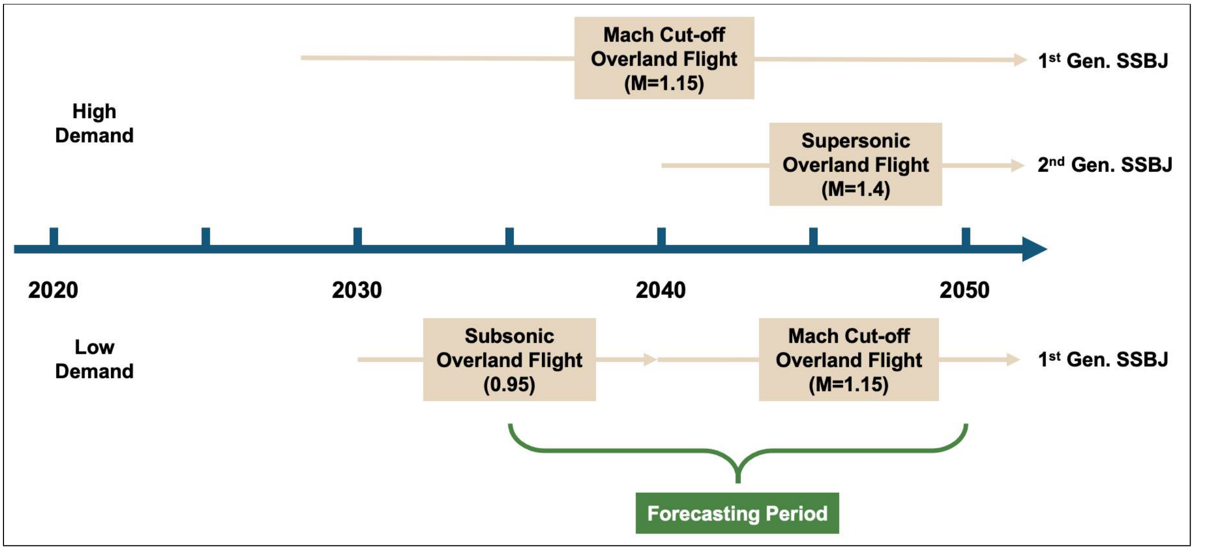


Fig. 7 Timeline for Supersonic Business Flight Operations

2. SSBJ Trip Time Estimation

The researchers used a regression-based method to estimate the mission block time for the SSBJ routes. Business jet flight data for a variety of routes was gathered using FlightAware's live flight tracking service [32] to construct a regression between block Mach number and great circle distance. This regression is then scaled for three different cruise Mach numbers: 0.95, 1.15, and 1.40. Using these regressions, block time for simple missions (flights with a single cruise segment at the specified Mach number) can be easily estimated.

However, supersonic flights in the real world are usually more complicated than the typical subsonic missions with one cruise segment only. To provide quick trip time estimates without flight path planning, a weighted average method is used, with the over-land ratio (R) being the weighting factor. For example, if a route's flight path is 40% over-land, then under the Mach cut-off scenario, mission block time will be given by $T_{MCO} = R \cdot T_{1.15} + (1 - R) \cdot T_{1.4}$ with $R = 0.4$. $T_{1.15}$ is the simple mission time for Mach cut-off flight and $T_{1.4}$ is the mission time for full supersonic flight. For intra-North America flights, various R values are used depending on the geographical location of the origin-destination pair. For example, flights between Hawaii and the west coast of the United States and Canada have R of 0, flights along the coastal states have R of 0.2, flights between inland states have R of 0, and the rest of the intra-North America flights have R of 0.8. For the rest of the world, two different overland ratios are estimated for each region pair, one applicable to domestic flights, the other applicable to international flights. It is less ideal for an SSBJ to deviate greatly from the great circle path due to its lower supersonic cruise speed (comparing to an SST).

D. Flight Demand Forecasting

Since the supersonic and subsonic business flight movements are assumed to be analogous, the supersonic flight network will evolve according to the subsonic network. The main purpose of this section is to forecast business aviation growth, allowing the supersonic segment of business aviation to be more reasonably estimated. One good indicator for growth is fleet size, especially the number of medium to ultra-long-range jets, since this portion of the market is the most relevant to SSBJs. The research team was not able to find any long-term, region-level forecast for business aviation fleet growth in published literature, so an approach is needed to forecast fleet growth. This estimate considers the size of the existing fleet, as well as the differences in economic activities around the world. The outcome of this element also enables the researchers to make adjustments to the flight movement data for future years. The introduction of SSBJ is likely to open up a whole new market segment instead of competing with any existing segment, mainly because of its unique capability and high price point. How the supersonic flights might impact the subsonic segment is not explicitly considered in this study.

1. The Three Factors for Business Aviation Growth Forecasting

After multiple discussions and iterations, the following factors are considered when forecasting business aviation growth (reflected in terms of medium-ULR jet fleet growth). These three factors are the behavior of general economies in terms of GDP per capita, historical business jet fleet, and millionaire population. They are summarized in Figure 8:

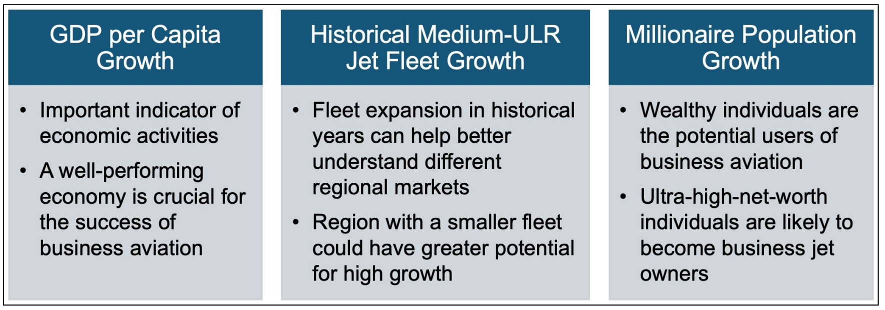


Fig. 8 The Three Factors for Forecasting Business Aviation Growth

On the region-level, a strong correlation between GDP per capita growth and business jet fleet growth is observed. The GDP data used in this study is provided by IHS Markit [33], which contains both historical data as well as forecast up to 2049. More specifically, this data is the real GDP per capita data at purchasing power parity, reported in 2015 US dollars. This is the only data set among the three forecasting factors that includes forecasted data, and it is scaled to forecast business jet fleet growth up to 2050. The historical medium-ULR jet fleet growth is taken into account, since future growth should (to some degree) be related to historical growth. The data here is obtained from various available reports by JetNet [24, 25]. However, the data is incomplete, and for some intermediate years, the growth is interpolated. Lastly, millionaire population growth is obtained from Credit Suisse's annual reports, which analyses the household wealth of 5.1 billion people across the globe [34]. The millionaire population is relevant to business aviation since this could be an indicator of the size of the potential client base.

2. Forecast Scaling Approach

A scaling factor (one for each region) is applied to the GDP per capita growth rates, so that the sum squared error between the scaled GDP per capita growth rates and the input data during historical years is minimized. A more detailed explanation of this process is shown in Figure 9 below:

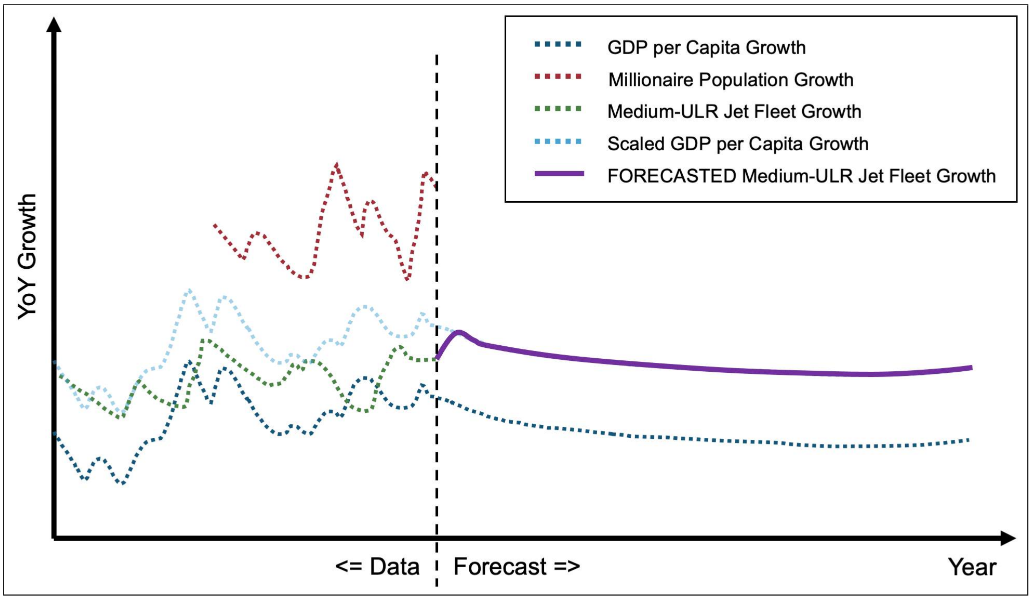


Fig. 9 Forecasting the Medium-ULR Jet Fleet Growth

The GDP per capita data used starts in the year 2003, and ends in 2049. The portion of data relevant for sum squared error calculation is between 2003 and 2018 (16 years total). The historical medium-ULR jet fleet growth data is also available from 2003 to 2018. Lastly, the millionaire population growth rates used are from 2011 to 2018 (8 years total). The next step is to find a scaling factor for the GDP per capita growth rates, such that the scaled values and the three sets of input data have the smallest sum squared error. The length of the input data naturally acts as a weighting factor when calculating sum squared error, with the following ratio: GDP per capita growth to fleet growth to millionaire growth = 2:2:1.

After the scaling ratios are calculated for each region, the results for the Asia-Pacific regions (mainland China, Asia, and Oceania) are fine-tuned after discussions with subject matter experts. For Asia and Oceania, the scaling factors are reduced by 20%, so that the future growth rates better match the historical growth rates. Additionally, Oceania is a more mature business aviation market and should experience slightly slower growth. For mainland China, the scaling factor is reduced by 30%. This reduction occurs because China's business aviation fleet started in 2003 [35] and experience rapid growth in the first decade. However, in recent years, China's fleet growth has been stagnant. Data is gathered from Asian Sky Media's report [36], with fleet data prior to 2007 extrapolated. Since China has very high millionaire growth and GDP per capita growth, the scaling factor computed was exaggerated because of these high growth rates.

Lastly, to smooth out the transition from historical growth rates to forecasted growth rates, a technique called exponential smoothing is used. For any time t, the smoothed value S_t is found by computing the following exponential smoothing equation: $S_t = \alpha y_{t-1} + (1 - \alpha) S_{t-1}$, where y is the original data value and α is the smoothing constant.

After fine-tuning and smoothing, the predicted long-term fleet growth rates for mainland China ranges between 7.5-9%, for Asia and Oceania, between 3%-4%, and for the rest of the regions, ranging from 1.5%-2.5%.

E. Medium-ULR Jet Movement

As explained in section III.D.2, medium to ultra-long-range jet movement data is sourced from FlightAware. By comparing the aggregated flight hours from the data to the fleet size of each region, it is clear that the data coverage for some regions is less ideal than others'. As a result, the flight pattern will need to be adjusted to reflect a more realistic network. Furthermore, since the business aviation growth (based on fleet growth) for each region is different in forecasted years, the movement pattern is also evolving. An optimization technique is used to compute a realistic flight movement network. The next section introduces the approach via a simple example.

1. Simple Flight Movement Network Example

In this 4-region network, each region's total flight hours is denoted by FH_i, where $i = 1 - 4$. Additionally, the R_{ij} terms ($i, j = 1 - 4$) represent the flight hour percentages. R_{11} means the flight hour percentage for movements within region 1, and R_{12} is that for flights from region 1 to region 2. For each region i, $\sum_{j=1}^{4} R_{ij} = 1$. In the real world, the flight hours from A to B and from B to A will not be equal due to various factors. However, in an idealized network, $FH_i \cdot R_{ij} = FH_j \cdot R_{ji}$ for all $i \neq j$, which means flight hours between a region pair should always balance.

For a network with 4 regions, the condition for flight hour percentages summing to 1 provides 4 equations, and the inter-region flight hour equality provides 6 equations (6 unique ways to choose a pair from 4 regions, C(4,2) = 6). However, even if the flight hour for each region is known, there are still 16 unknowns R_{ij} terms. Since there are more unknowns than equations, it is not possible to solve for the R_{ij} terms and obtain a unique solution, so an optimization technique should be used.

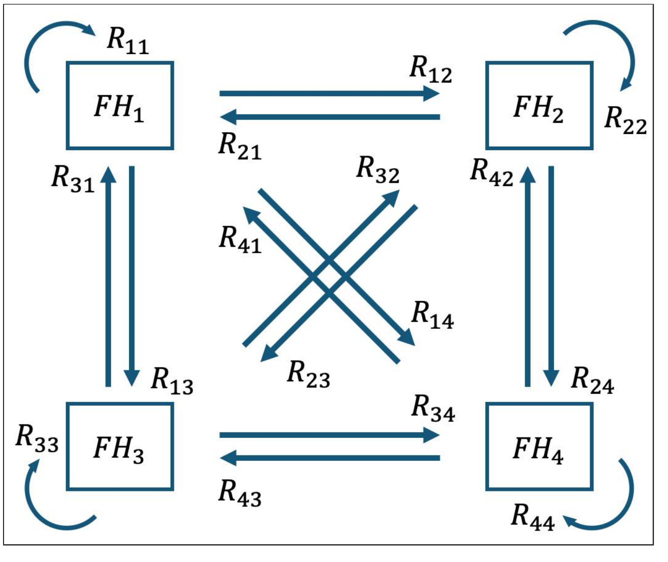


Fig. 10 4-Region Flight Movement Network

For this problem, the flight hour (FH_i) for each region is available from FlightAware's original network data and can be easily scaled. The R_{ij}'s for the original network is also available. However, when flight hour from each region is scaled differently, the flight hour equality condition between regions will no longer be valid, unless the R_{ij} terms are adjusted appropriately. The objective function is defined such that the sum squared error between R_{ij}'s before and after the adjustment is minimized. This means the solver will try to converge to a solution with minimal change from the original flight movement percentages.

2. Flight Movement Adjustment for FlightAware Data

The network formulated using the FlightAware data follows the same logic, but with 7 regions instead of 4. Additionally, some region pairs have no movements simply because they are too far apart. The optimization technique used is the generalized reduced gradient method. The solver obtained a solution that satisfied all the constraints for each year-scenario combination. However, since there is no unique solution, this approach only represents a valid solution at a local minimum of the objective function. The final result is carefully checked by the research team to ensure that the flight movement pattern and its progression over time is reasonable.

In terms of the vehicle range, the authors assumed a more flexible range of 4,500 nmi. In comparison, the NASA STCA concept has a supersonic range of roughly 4,250 nmi [37]. Business jets designed for Mach 1.4 are likely to be more efficient at subsonic speeds, so greater range is possible if part of the flight is spent cruising subsonically. Additionally, this study does not explicitly consider routes that require refueling, since this information is not available from the FlightAware movement data, and re-fueling will significantly reduce SSBJ's time advantage. All the routes aggregated at the region level for flight movement adjustment meet the following criteria:

- Have a great circle distance between 150 and 4,500 nmi
- The longest runway at both the origin and destination airports exceed 6,000 feet

F. Supersonic Business Jet Movement Construction

1. Generating SSBJ Routes

For a given scenario in a given year, the top-down portion of the methodology estimates the total available flight hours for the SSBJ. From the bottom-up portion, the flight network for subsonic, medium-ULR jets is adjusted and forecasted, with flight hour percentages calculated for each region pair. Naturally, the remaining steps are to assign the flight hours to each region pair base on the calculated flight hour percentages, then further distribute the flight hours to routes within each region pair. Once the total flight hours for a route is known and flight time is calculated, the number of annual flights for that route can be estimated. Due to data coverage issues, some region pairs simply do not have enough representative routes to generate airport-level results. However, region pairs with routes reported still account for roughly 82% of the total flight movements in terms of flight hours.

2. Cut-Off Criteria and Sensitivity Analysis

When the total flight hours are assigned to a route and the number of flights annually is calculated, a route becomes feasible for SSBJ operations if it has more than one flight in a given year. The time-saving aspect of supersonic flight has not been considered yet. Time-saving could be important both in relative and absolute terms, and different user groups could have different requirements for minimum time savings.

Sensitivity analysis is a useful technique for evaluating the impact of different inputs or criteria on the result. To decide whether or not to include a specific route in the forecasted SSBJ flight movement, the following minimum cut-off criteria are considered:

1) Minimum trip frequency: business aviation flights are known for their wide range of O/D airport pair selections but relatively low frequency for individual airport pairs
2) Minimum absolute time savings: evaluate the absolute time savings achieved by an SSBJ
3) Minimum relative time savings: evaluate the relative time savings achieved by an SSBJ

After the final list of O/D pairs is generated, the left-over flight hours from the cut-off are re-distributed to the airport pairs that satisfy the cut-off criteria.

First, the number of annual SSBJ flights is considered. The SSBJ fleet is going to be much smaller than the subsonic business jet fleet. When flight hours are assigned to the route-level, many routes do not have many flights annually. Figure 11 and Figure 12 show the number of weekly flights for the routes that satisfy the cut-off criteria. The number of weekly flights is plotted instead of the number of routes, because if a very popular route is removed, the impact on the number of flights will be much more significant compared to the number of routes.

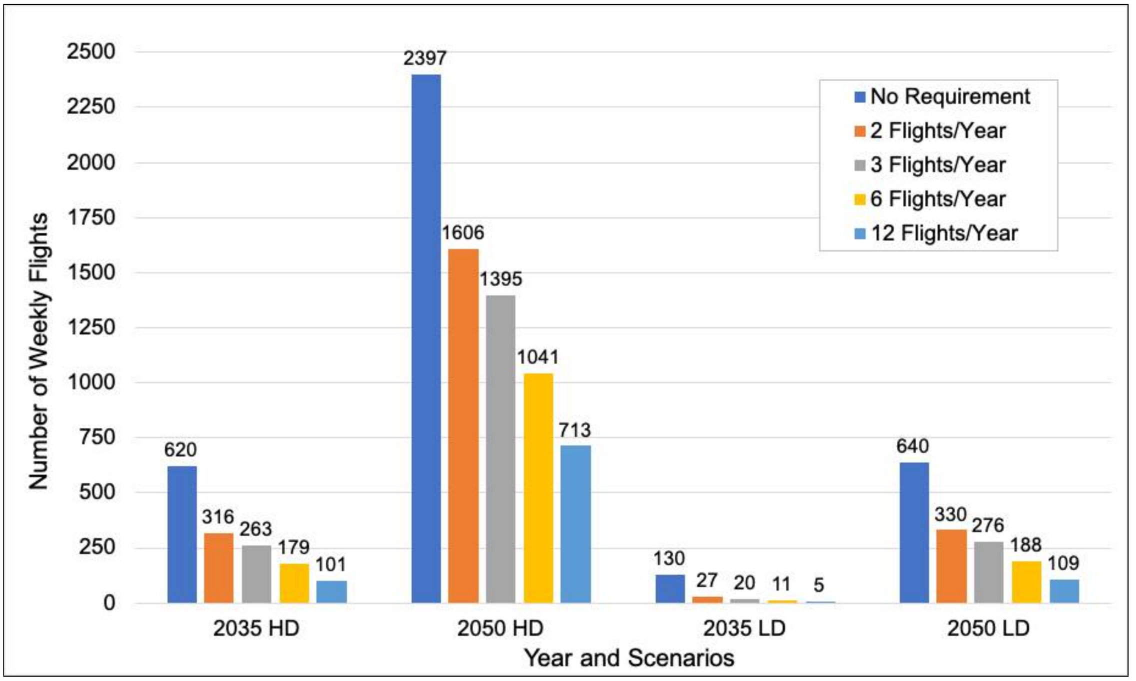


Fig. 11 Effect of Minimum Trip Frequency Criterion on Intra-North America SSBJ Routes

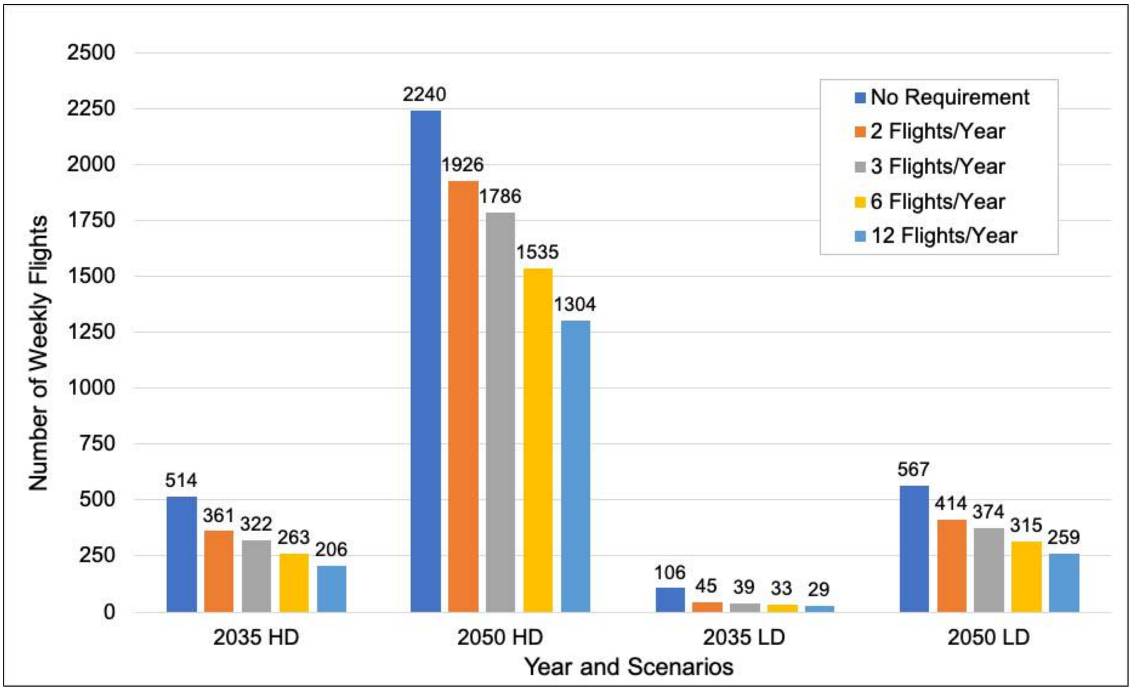


Fig. 12 Effect of Minimum Trip Frequency Criterion on SSBJ Routes in the Rest of the World

Comparing the results for intra-North America vs. the rest of the world, it is easy to see that North American routes are more affected by the minimum trip frequency requirement, which means that many routes in North America are not flown frequently. The next step is to evaluate the impact of time savings criteria. Figure 13 and Figure 14 show how the absolute and relative time savings requirements reduce the frequency of viable SSBJ flights.

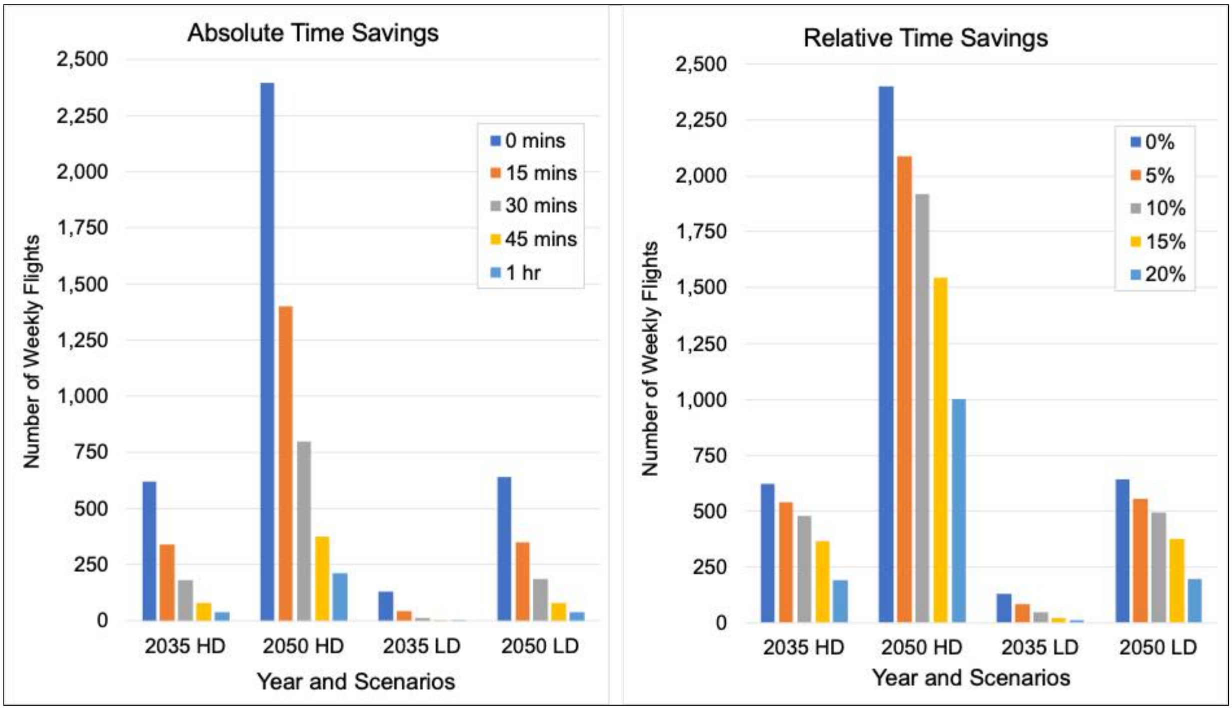


Fig. 13 Effect of Absolute and Relative Time Savings on Intra-North America SSBJ Routes

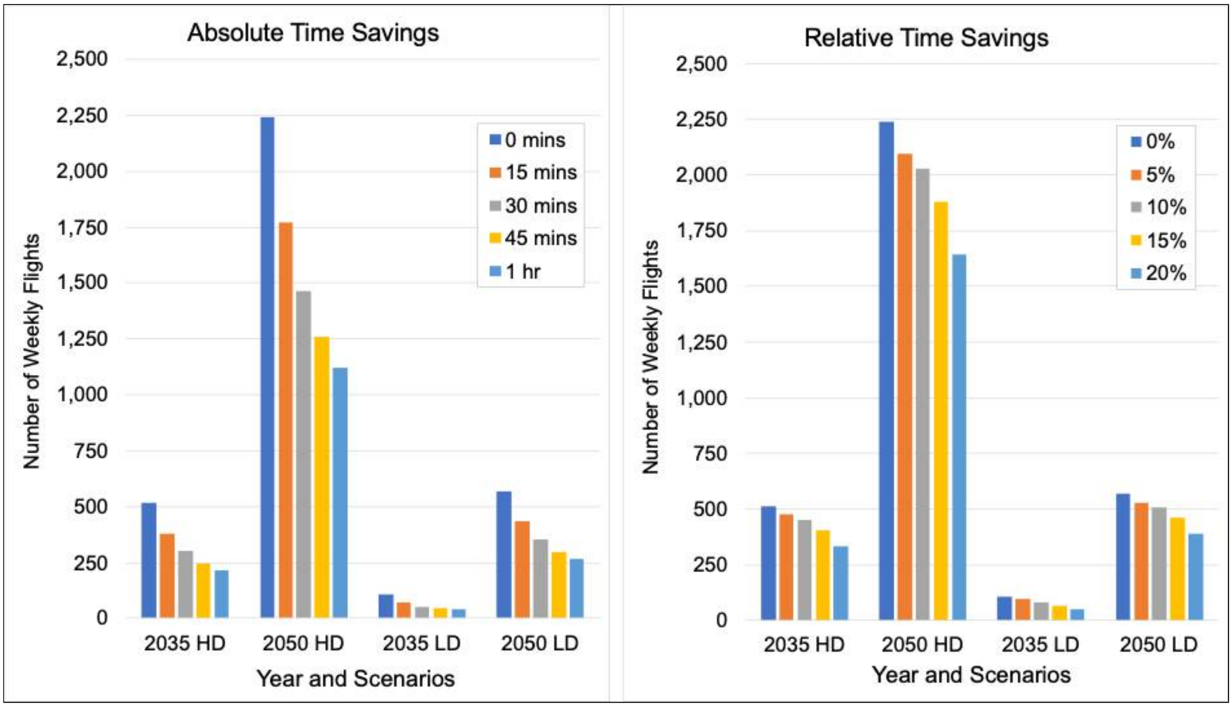


Fig. 14 Effect of Absolute and Relative Time Savings on SSBJ Routes in the Rest of the World

Again, it is quite easy to notice that North American routes are more affected by time savings requirements than the rest of the world. This is mainly due to the large landmass of the North American continent. This analysis shows that the absolute time advantage that an SSBJ can provide on most routes is limited for intra-North America flights. Imposing 15 minutes of required time savings filters out almost half of the movements in the North American region. A similar trend is observed for other region pairs as well. Relative time savings have less impact on the number of viable flights.

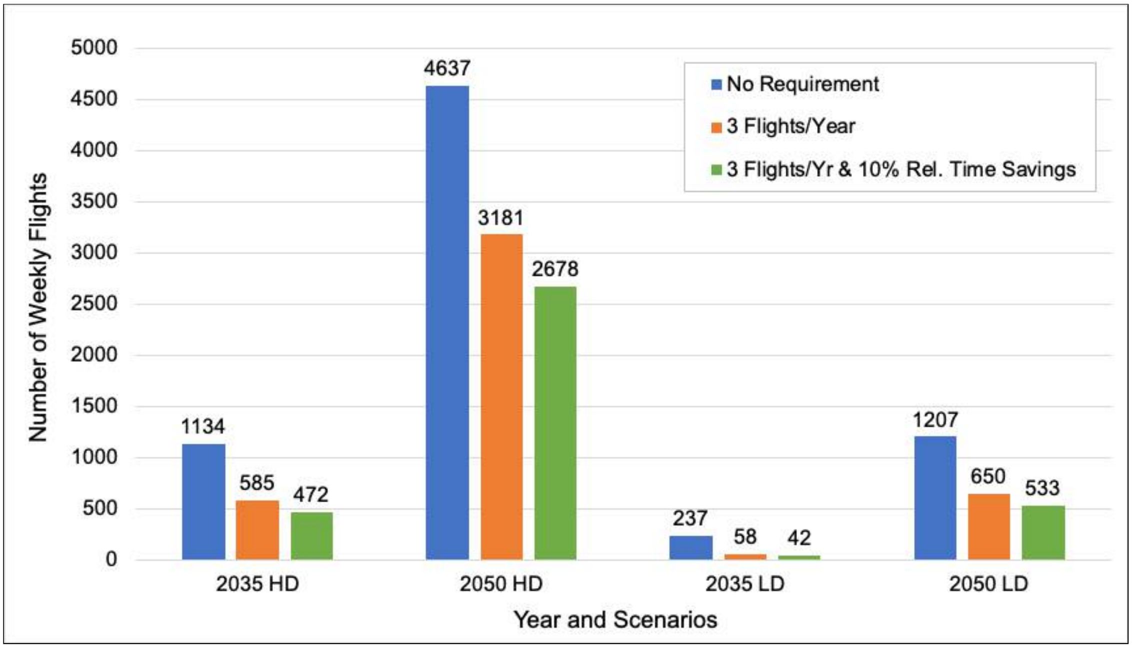


Fig. 15 Effect of the Chosen Cut-Off Criteria on the Global Set of Routes

Finally, the criteria selected are 3 minimum flights per year and 10% relative time savings. Figure 15 illustrates the impact of these cut-off criteria. The two cut-off criteria heavily impacted the number of viable flights for the low demand scenario in 2035 since supersonic over-land flight is not permitted and the available SSBJ flight hours are low. The left-over flight hours due to cut-off criteria will be re-distributed among the viable routes, so that the total SSBJ flight hours match the projected value.

3. Accounting for Overhead Flights

As explained in Section III.D.1, in this study, routes above 150 nmi are considered for airport-level SSBJ flight movements. However, flights below 150 nmi contribute significantly to the total number of business jet flights. Such flights are categorized as "overhead" in this study. Overhead flights can exist in intra-region movements as well as bordering regions. Since the distance is so short, the aircraft might not even reach its cruise speed before it needs to slow down and prepare for landing. The speed advantage and the resulting time savings will not be reflected on shorter flights, but they are sometimes necessary. As a result, these short overhead flights will increase the number of flights calculated for certain region-pairs. However, a percentage reduction will be applied to the current overhead flight portions calculated based on the FlightAware data. For high demand, there is a 50% reduction. For low demand, the reduction increases to 66%.

The airport runway length requirement is considered when calculating the percentage of overhead flights as well, just like the normal flights. These overhead flights increase the number of flights on the region level, and are not affected by the cut-off scenario. This concludes the section for the SSBJ flight movement construction. In the following section, the results of this study are presented at both global and regional levels.

VI. Results

A. Number of Daily Flights by SSBJ

Figure 16 shows the estimated number of daily SSBJ flights from entry-into-service to 2050:

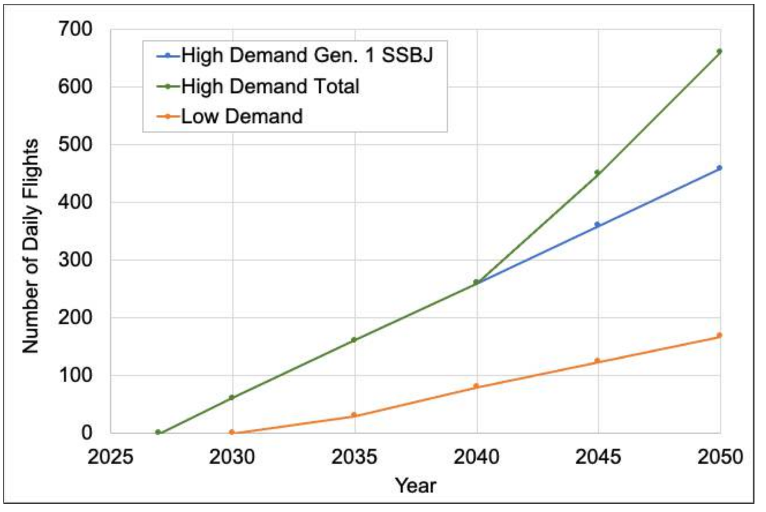


Fig. 16 Forecasted Number of Daily Flights by SSBJs

The growth trend for the number of daily flights is similar to the vehicle demand shown in Figure 5. This result is not surprising since the number of daily flights is closely related to the flight hours available. For the high demand scenario, the second-generation SSBJ with low-boom technology increases the number of flights due to the additional flight hours it introduces. In the low demand scenario, the relaxation of over-land flight restriction in the year 2040 led to a slight increase in the growth of daily flights. This is because even though Mach cut-off overland flight reduces the flight time for most trips and increases productivity (so more flights can be flown), no new flight hours are added.

B. Number of Routes Served by SSBJ

The following figure shows the estimated number of routes served by SSBJ at the airport level from 2030 to 2050. Since airport-level results are reported on roughly 82% of the global business aviation market, the actual number of routes (or airport pairs served) will be higher. Flights from A to B and from B to A are counted separately.

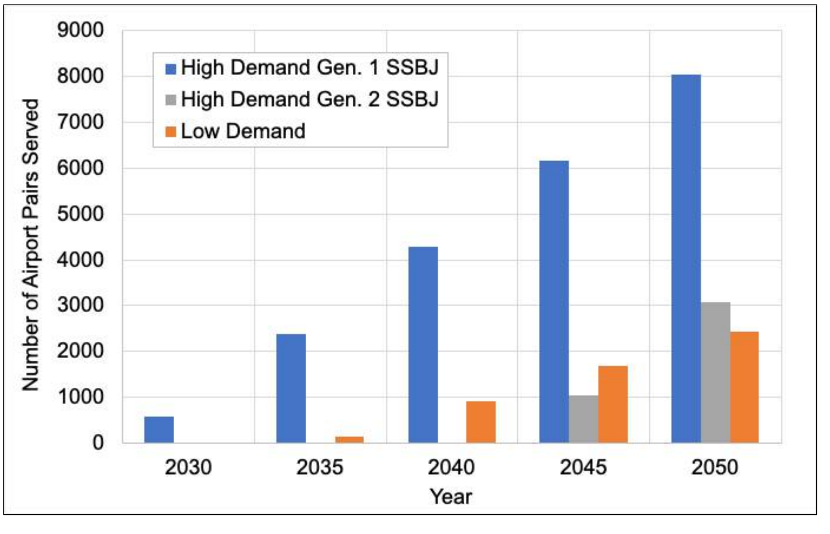


Fig. 17 Forecasted Number of Routes Served by SSBJs

In Figure 17, it can be seen that the network will be much less significant if the supersonic over-land flight ban remains in place (due to the low number of routes served for the low demand scenario in 2035). Looking at the high demand scenario, the number of routes served by first-generation SSBJ and second-generation (low-boom) SSBJ are listed separately. The research team checked the number of routes served exclusively by low-boom SSBJ in 2050 (the number of routes that become viable because of low-boom full speed over-land flight), and it is only 228 routes. This is likely due to the low requirement for time savings. If an absolute time savings requirement is imposed (even if it is only 15 or 30 minutes), the result would show more routes enabled by Mach 1.4 over-land flight.

Table 6 Number of SSBJ Routes by Region Pairs

Scenario	High Demand							Low Demand			
	Gen. 1 SSBJ					Gen. 2 SSBJ					
Region Pair \ Year	**2030**	**2035**	**2040**	**2045**	**2050**	**2045**	**2050**	**2035**	**2040**	**2045**	**2050**
N. America-N. America	323	1354	2398	3453	4516	608	1780	77	511	956	1402
Europe-Europe	146	529	946	1349	1700	239	654	27	219	377	526
Asia-Asia	57	189	320	455	554	114	259	12	81	132	183
Oceania-Oceania	2	17	32	46	61	4	19	2	2	4	7
N. America-Europe	9	34	70	113	161	12	38	3	13	27	35
N. America-L. America	13	62	135	198	257	20	81	4	20	46	72
Europe-Asia	5	52	89	120	183	14	58	1	14	33	49

C. Samples of Forecasted Routes

Some sample routes are provided in this section. All the routes are plotted using a simple online tool [38]. Please note that the routes on these figures are not intended to illustrate the supersonic flight paths. Figure 18 shows the forecasted routes served by first-generation supersonic business jets between North America and Europe in 2035:

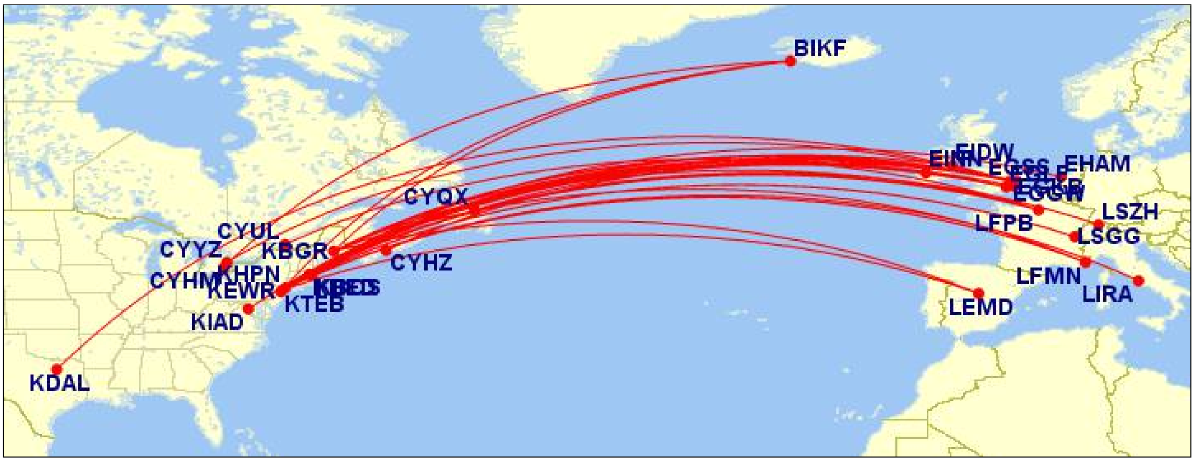
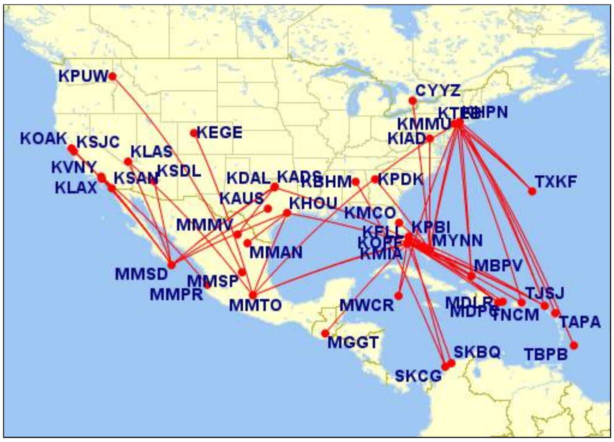
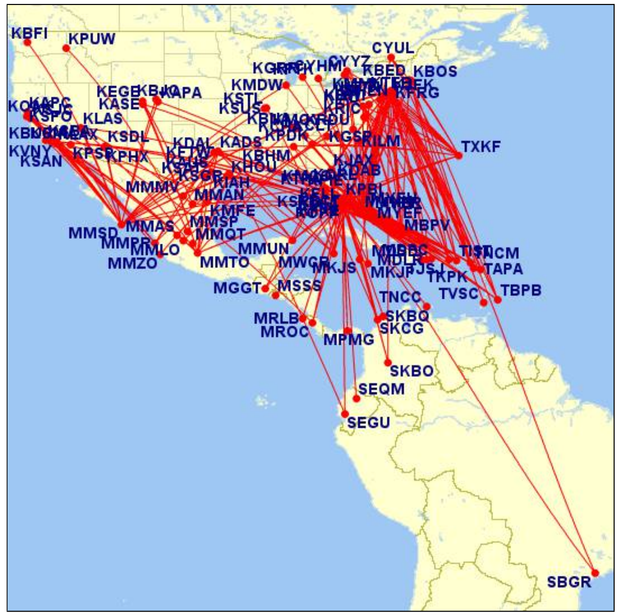


Fig. 18 Forecasted Routes between Europe and North America, Year 2035, High Demand, Gen. 1 SSBJ

Figure 19a and Figure 19b show the growth of the entire forecasted SSBJ network between North America and Latin America in 2035 and 2050.



(a) Year 2035



(b) Year 2050

Fig. 19 All Routes between North America and Latin America, High Demand, Gen.1 SSBJ

The majority of routes served by a first-generation SSBJ compared to those served by a second-generation SSBJ are quite similar due to the relatively relaxed time-saving requirement. If an additional constraint for absolute time savings is imposed, or the relative time-saving requirement is increased, some new routes would become available since they can take advantage of low-boom SSBJ's higher over-land cruise speed.

VII. Conclusion

A. Summary of the Forecasting Methodology

In this supersonic business flight movement forecast, the authors took the unique characteristics of business aviation (many use cases, different aircraft ownership, a large number of routes covered, etc.) and the requirements from the Topic Leader (airport-level movement forecast desired) into consideration and created a methodology that combines the benefits of both top-down and bottom-up forecasting methods. The business aviation growth is forecasted at the regional level using historical fleet growth, real GDP per capita growth, and global millionaire population growth. To better understand the business flight network and global flight movement pattern, subsonic unscheduled flight movement data is acquired from FlightAware. Due to poor data coverage in certain regions, the flight movement pattern is adjusted based on fleet size and estimated aircraft utilization, then solved using an optimizer. In the end, the movement forecast is reported at the airport-level for regions with good data coverage. For regions with relatively poor coverage, the number of flights is reported at the region-pair level.

B. Summary of Results and Key Takeaways

Table 7 summarize the results of the study on a global level:

Table 7 Number of Daily Flights and Routes Served by SSBJs

Scenario	High Demand		Low Demand	
Metric \ Year	**2035**	**2050**	**2035**	**2050**
Number of Daily Flights by SSBJs	160	661	30	167
Number of Routes Served by SSBJs	2383	8259	134	2427

The research team identifies three major takeaways based on the outcomes of this study:

1) Even when the time-saving requirement is very low (10% relative time savings), the market is insubstantial if the SSBJ must travel subsonically (M = 0.95) over-land.
2) The added benefit of low boom full-supersonic (M = 1.4) over-land flight is not as significant as expected (in terms of the number of routes unique to the low boom SSBJs). This may be the result of the modest time savings requirement.
3) Improved ADS-B global data coverage will improve the accuracy of the forecasted supersonic business routes and the number of movements.

C. Comparing to Supersonic Commercial Aviation

It is also interesting to compare the outcome of supersonic business aviation forecast to supersonic commercial forecast. In terms of the estimated number of daily flights in 2035 and 2050, the estimates are on the same order of magnitude. However, the number of routes served by SSBJs is estimated to be one order of magnitude higher than the routes served by commercial supersonic transport [5]. As a result, the key characteristic of business aviation (unscheduled) movements is well-reflected.

D. Future Work

There are a few areas that are worth considering for future work. The first area is the comprehensiveness of subsonic baseline data for the business aviation network. If ADS-B data coverage greatly improves in the next few years, it might be beneficial to conduct similar studies again with more representative subsonic baseline movement data.

In addition, other companies (such as JetNet and WING-X) could potentially provide region-level movement estimates for business aviation globally, which would enable more accurate scaling of the FlightAware movement data (instead of the approach based on fleet size and annual utilization used in this study). Alternatively, better estimates of region-level annual aircraft utilization could also improve the forecast.

This study uses a simple regression-based method to estimate the SSBJ trip time. Higher fidelity methods that consider both aircraft performance and flight routing can provide more accurate estimates regarding the time advantage of supersonic business jets.

An SSBJ should consume less fuel and emit less amount of pollutants than a commercial supersonic transport (SST) since the SSBJ is smaller and is expected to have a lower supersonic cruise Mach number. However, since the number of daily SSBJ flights is estimated to be on the same level as SST flights [5], it would be interesting to compute the fuel burn and emissions for an SSBJ network for comparison.

VIII. Acknowledgments

This project has received funding from the Clean Sky 2 (CS2) Joint Undertaking (JU) under grant agreement No.864521. The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Clean Sky 2 JU members other than the Union. This project was carried out by the Aerospace Systems Design Laboratory at Georgia Tech Lorraine (ASDL@GTL) in Metz, France, under the Georgia Tech – CNRS (Centre National de la Recherche Scientifique) UMI 2958 (Unités Mixtes Internationales) research partnership. The authors dedicate special thanks to Ralf Berghof and Nico Flüthmann of the German Aerospace Center (DLR) for their guidance and support. The authors would also like to express gratitude to members of the OASyS Advisory Board, Dr. Holger Pfaender and Dr. Elena Garcia, as well as members of the OASyS team, Colby J. Weit, Akshay Anand, and Harleen Kaur, for their important contributions. The results and discussion published in this paper are only the views of the authors and do not reflect the views or opinions of DLR nor the CS2JU.

References

[1] "Concorde Grounded for Good," *BBC News*, 2003.

[2] Dourado, E., and Hammond, S., "Make America Boom Again: How to Bring Back Supersonic Transport," the Mercatus Center at George Mason University, 2016.

[3] Liebhardt, B., Lütjens, K., and Gollnick, V., "Estimation of the Market Potential for Supersonic Airliners via Analysis of the Global Premium Ticket Market," *11th AIAA Aviation Technology, Integration,and Operations (ATIO) Conference*, 2011. https://doi.org/10.2514/6.2011-6806.

[4] Liebhardt, B., Lütjens, K., Tracy, R. R., and Haas, A. O., "Exploring the Prospect of Small Supersonic Airliners – A Business Case Study Based on the Aerion AS2 Jet," *17th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, 2017. https://doi.org/10.2514/6.2017-3588.

[5] Wen, J., Weit, C. J., Mayakonda, M., Anand, A., Zaidi, T., and Mavris, D., "A Methodology for Supersonic Commercial Market Estimation and Environmental Impact Evaluation (Part II)," *AIAA AVIATION 2020 FORUM*, 2020. https://doi.org/10.2514/6.2020-3261.

[6] Jain, S., Ogunsina, K. E., Chao, H., Crossley, W. A., and DeLaurentis, D. A., "Predicting Routes for, Number of Operations of, and Fleet-level Impacts of Future Commercial Supersonic Aircraft on Routes Touching the United States," *AIAA AVIATION 2020 FORUM*, 2020. https://doi.org/10.2514/6.2020-2878.

[7] "Economic Impact of Business Aviation in Europe," Booz Allen Hamilton and DLR, 2016.

[8] "Business Aviation Fact Book," National Business Aviation Association, 2014.

[9] Krane, D., and Orkis, K., "The Real World of Business Aviation: A Survey of Companies Using General Aviation Aircraft," Harris Interactive, 2009.

[10] "Average Daily Block Hour Utilization of Total Operating Fleet," Massachusetts Institute of Technology, 2018.

[11] "Air Carrier Summary: T2: U.S. Air Carrier Traffic And Capacity Statistics by Aircraft Type," Bureau of Transportation Statistics, 2019.

[12] "Business Aviation Index - Q2 2019," Jet Support Services Inc, 2019.

[13] "European Business Aviation - Economic Value & Business Benefits," European Business Aviation Association, 2018.

[14] Broderick, S., "Teterboro Reiterates Heavy Aircraft Permission Procedures," *AIN Online*, 2017.

[15] Lynch, K., "Supersonic AS2 Just a Starting Point for Aerion," *AIN Online*, 2020.

[16] Lynch, K., "Aerion Paving Path To Bring AS2 to Market," *AIN Online*, 2020.

[17] Benson, L. R., "Quieting the Boom - The Shaped Sonic Boom Demonstrator and the Quest for Quiet Supersonic Flight," National Aeronautics and Space Administration, 2013.

[18] Howe, D., Simmons III, F., and Freund, D., "Development of the Gulfstream Quiet Spike for Sonic Boom Minimization," *46th AIAA Aerospace Sciences Meeting and Exhibit*, 2008. https://doi.org/10.2514/6.2008-124.

[19] Hemmerdinger, J., "NASA and Lockheed to Begin X-59 Supersonic Jet Tests in 2021," *FlightGlobal*, 2020.

[20] Trautvetter, C., "JetNet: Market for Supersonic Bizjets Sizable, Growing," *AIN Online*, 2019.

[21] "Business Aviation in Europe 2009 - EUROCONTROL Trends in Air Traffic, Volume 6," EUROCONTROL, 2009.

[22] "FlightAware Custom Reports," FlightAware, 2020.

[23] "FlightAware and ADS-B," FlightAware, 2020.

[24] "JETNET iQ Market Report – 2019," JetNet, 2019.

[25] "JETNET iQ Snap! Q1 2014 Summary Report," JetNet, 2014.

[26] "Fleet Report YE2019," Asian Sky Group, 2019.

[27] "2018 Business Aviation Review," ARGUS International, 2019.

[28] "10-Year Business Aviation Market Forecast 2018-2027," Jetcraft, 2018.

[29] Wynbrandt, J., "Charter Market Report 2018," *AIN Online*, 2018.

[30] FAA, "Special Flight Authorizations for Supersonic Aircraft," Federal Register, 2019.

[31] FAA, "Noise Certification of Supersonic Airplanes," Federal Register, 2019.

[32] "FlightAware Live Flight Tracking," FlightAware, 2020.

[33] "Economics & Country Risk," IHS Markit, 2020.

[34] "The Global Wealth Report," Credit Suisse, 2020.

[35] You, T., "Flying Dragons: Private Jets are New Status Symbol in China," *CNN Travel*, 2012.

[36] "The Greater China Business Jet Fleet YE 2012," Asian Sky Group, 2012.

[37] Berton, J. J., Huff, D. L., Geiselhart, K., and Seidel, J., "Supersonic Technology Concept Aeroplanes for Environmental Studies," *AIAA Scitech 2020 Forum*, 2020. https://doi.org/10.2514/6.2020-0263.

[38] Swartz, K. L., "Great Circle Mapper," *gcmap.com*, 2020.